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RESEARCH MEMORANDUM

EFFECT OF PRESSURE ON THE SMOKING TENDENCY

OF DIFFUSION FLAMES

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SUMMARY

The effect of pressure on smoke formation was investigated by burning nine hydrocarbon fuels as diffusion flames from a modified wick lamp in an enclosed chamber. The maximum relative rate at which each fuel could be burned without smoking was determined over a pressure range of about 1/2 to 4 atmospheres, and up to 12 atmospheres in the case of one fuel. The results indicate that over this pressure range the maximum smoke-free fuel flow was inversely proportional to the pressure. The relative variation in smoking tendency among the different fuel types was approximately constant at all pressures. From an analysis of the data it has been tentatively proposed that the variations in smoke formation with pressure result from changes in the rate of diffusion and mixing of the fuel and air.

INTRODUCTION

The variations in smoking tendency with fuel type at atmospheric pressure have been reported by several investigators (refs. 1, 2, and 3). However, investigations of smoking tendencies at pressures other than atmospheric have been very limited. Parker and Wolfhard (ref. 4) have observed that smoke formation from an acetylene flame decreased with decreasing pressure, and Smith (ref. 5) noted in a spectroscopic study of an ethylene flame that smoke formation became more pronounced at elevated pressures.

In order to obtain a more comprehensive understanding of the effect of pressure on smoke formation, an investigation was conducted at the NACA Lewis laboratory to determine the variations in smoking tendency over a wide range of pressures for a variety of fuels.

In the present study, six pure hydrocarbon compounds, a JP-4 fuel, and two blends of octane and toluene were investigated over a pressure range of about 1/2 to 4 atmospheres. For two of the hydrocarbons, namely, octene-1 and n-octane, the pressure range was extended to 9 and 12 atmospheres, respectively. Smoking tendencies were determined by burning the fuels as diffusion flames from a modified wick lamp in an enclosed chamber. The maximum relative rate at which the fuels could be burned without smoking was used as the criterion of smoking tendency.

APPARATUS AND PROCEDURE

A sketch of the apparatus used to study the effect of pressure on smoke formation is shown in figure 1. The chamber in which the fuels were burned was approximately 30 centimeters in diameter and 70 centimeters high. To obtain pressures above atmospheric, service air was admitted at the bottom of the chamber through perforated holes in a circular copper manifold. To remove the combustion products, a constant air exhaust of 220 milliliters per second was maintained at all pressures. The exhaust rate was measured by a flowmeter connected to the exhaust valve on the lid of the chamber. It was found that appreciable variations could be made in the exhaust rate without changing the smoking tendency of the flame. To obtain pressures below atmospheric, a vacuum line was connected to the exhaust valve and the flowmeter was attached to the air intake line. As a safety precaution and as a means of extinguishing the flame, gaseous carbon dioxide could be admitted to the chamber through a valve in the center of the lid.

The fuels were burned from a wick lamp which consisted of a 1.5-centimeter-inside-diameter glass tube 8 centimeters high to which was sealed a calibrated side arm. A hydraulic jack, operated from outside the chamber, permitted the raising and lowering of the wick lamp through a supporting collar. The rate of fuel flow needed to attain the smoking point could be controlled by adjusting the height that the wick extended above this support collar. A chimney 18 centimeters high and 4.7 centimeters in diameter was placed with the bottom edge level with the wick tip to keep the flame erect and stable. The smoking point of the diffusion flame was observed visually through a 2.54-centimeter Lucite window on the front of the chamber.

The rate at which the fuel could be burned smoke-free was determined by measuring the time required for the level of the fuel in the side arm of the wick lamp to drop a unit distance while the fuel was being burned just below its incipient smoking point. The side-arm scale was calibrated against water; the fuel flow rates in grams per second could be obtained from this calibration and the specific gravity of the fuel. Reproducibility of the order of ±3 percent was obtained by this procedure.

Since variation in the size and position of the chimney and other changes in the geometry of the setup will change the smoking tendency of the flame, the data from this study are relative.

Fuels. - All the hydrocarbon compounds studied were of a purity of 97 percent or greater. The two blends of n-octane and toluene were based on volume percent. Pertinent properties of the JP-4 fuel studied are shown in the following table:

Fuel properties	MIL-F-5624A, grade JP-4 (NACA fuel 52-53)
A.S.T.M. distillation D86-46, ^{O}F	
Initial boiling point	136
Percent evaporated	
5	183
10	200
20	225
30	244
40	263
50	278
60	301
70	321
80	347
90	400
Final boiling point, ^{O}F	498
Residue, percent	1.2
Loss, percent	0.7
Specific gravity at $60^{O}F/60^{O}F$	0.757
Reid vapor pressure, lb/sq in.	2.9
Hydrogen-carbon ratio by weight	0.170
Net heat of combustion, Btu/lb	18,700
Aromatics, A.S.T.M. D-875-46T,	
percent by volume	8.5

RESULTS AND DISCUSSION

The fuels employed in the present investigation and the maximum smoke-free fuel flow at each pressure studied are given in table I. In figure 2(a) the maximum rates (g/sec) at which the six pure hydrocarbon compounds could be burned smoke-free are plotted against pressure. The pressure range was extended for two of the compounds and these results are shown in figure 2(b). In figure 2(c) the maximum rates for 100 percent n-octane, two blends of n-octane and toluene, and a JP-4 fuel are plotted against pressure. As can be observed from figure 2, the rates at which the fuels can be burned smoke-free consistently decreases with increasing pressure. The JP-4 fuel and the two blends of n-octane and toluene show the same variation in smoke formation with pressure as do the pure hydrocarbon compounds.

The general shape of the curves in figure 2 suggests that they might fit the equation for a rectangular hyperbola, xy = k. The product of the pressure and smoke-free fuel flow should therefore be a constant (k) at all pressures. The values of k obtained from the data are presented in table I. If some allowance is made for experimental errors, it would

appear that the values of k are reasonably constant for each fuel. The n-octane data, however, indicate that above 5.5 atmospheres, the $xy = k$ relation is no longer satisfactory. Consequently, the use of this equation should be restricted to the pressure range of about 1/2 to 5 atmospheres. Knowing the smoke-free fuel flow of a given fuel at any pressure within this range will permit an evaluation of k for that fuel. The smoke-free fuel flow at 1 atmosphere would, of course, be equal to k. Once k is obtained, the smoke-free fuel flow at other pressures may be readily calculated with an accuracy sufficient for most practical purposes.

In table II a comparison is made between the smoke-free fuel rate of n-octane and octene-1 over a pressure range of 1 to 10 atmospheres. At 1 atmosphere, twice as much n-octane can be burned smoke-free as octene-1, and at all pressures up to 10 atmospheres this same proportion is found to be approximately constant. A similar comparison among the other fuels also showed a fairly constant ratio over the pressure range investigated. Consequently, the same relative variations in smoke formation among different fuel types existed at all the pressures investigated.

In an attempt to explain the variations in smoke formation with pressure, several features of the diffusion flame were studied. Consideration was first given to the effect of pressure on flame size. In agreement with the postulations of Parker and Wolfhard (ref. 4) it was observed that the height of a nonsmoking diffusion flame was essentially independent of pressure and proportional to the mass flow. For example, at 1 atmosphere a fuel flow of 1.8 grams per second supported a nonsmoking flame of n-octane 3.5 centimeters high. At both 1/2 and 2 atmospheres this same fuel flow again supported a nonsmoking flame 3.5 centimeters high. Thus, increases in pressure, over the range investigated, do not cause a change in the flame height providing a constant mass fuel flow is maintained.

Since the flame volume and surface area are roughly proportional to the flame height, the volume and surface area of the flame cone are also independent of pressure and proportional to the mass flow. Consequently, the variation in smoke formation with pressure cannot be directly attributed to changes in the surface area or volume of the flame.

One of the factors which changes with pressure is the rate of diffusion and, consequently, the rate of mixing (ref. 4). Since the fuels were burned as diffusion flames in this study, the change in rate of diffusion and mixing should be taken into consideration in any explanation regarding increased smoke formation with pressure. It is reported in reference 4 that the diffusion coefficient is inversely proportional to the pressure, $D \sim 1/P$. If diffusion processes are the controlling factor, the smoke-free fuel flow should also be inversely proportional to the pressure. To observe how closely this relation is followed, a plot of

smoke-free fuel flow against $1/P$ is shown in figure 3. The fairly straight lines obtained in these plots establish that the smoke-free fuel flow is inversely proportional to the pressure. Therefore, the change in the diffusion process, which controls the rate of mixing, may account for the variation in smoke formation with pressure.

SUMMARY OF RESULTS

An investigation of the variation in smoke formation among hydrocarbon fuels over a pressure range of $1/2$ to 12 atmospheres gave the following results:

1. Over the pressure range studied, the amount of fuel which could be burned smoke free was inversely proportional to the pressure; however, the relation appeared somewhat less precise above 5 atmospheres.

2. The same relative variation in the smoke-free fuel flow among the different fuel types existed at all pressures.

3. The decrease in the rate at which the fuels could be burned smoke free with increasing pressure was attributed to the decrease in the rate of diffusion and mixing of the fuel and air.

Lewis Flight Propulsion Laboratory
        National Advisory Committee for Aeronautics
                Cleveland, Ohio, April 16, 1953

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6

TABLE I. - VARIATION IN SMOKE-FREE FUEL FLOW WITH PRESSURE

Pressure, atm	Fuel flow, g/sec	k^a	Pressure, atm	Fuel flow, g/sec	k	Pressure, atm	Fuel flow, g/sec	k
Isooctane (2,2,4-trimethylpentane)			90 percent n-octane +10 percent toluene			80 percent n-octane +20 percent toluene		
0.65	2.80×10^{-3}	1.8×10^{-3}	0.85	3.35×10^{-3}	2.9×10^{-3}	0.56	2.69×10^{-3}	1.5×10^{-3}
1.04	1.89	2.0	1.12	2.33	2.6	1.05	1.44	1.5
1.48	1.33	2.0	1.51	1.72	2.6	1.53	.96	1.5
2.11	.86	1.8	2.53	1.01	2.6	1.37	.67	1.6
2.64	.78	2.1	3.18	.92	2.9	3.35	.60	2.0
3.07	.73	2.2	3.76	.82	3.1		Average	1.6
3.80	.65	2.5		Average	2.8			
	Average	2.1						
Cyclohexene			2-methyloctane			JP-4		
0.62	2.43×10^{-3}	1.5×10^{-3}	1.04	3.85×10^{-3}	4.0×10^{-3}	0.56	2.42×10^{-3}	1.4×10^{-3}
1.04	1.29	1.3	1.38	2.81	3.9	1.26	1.04	1.3
1.21	1.09	1.3	1.78	2.13	3.8	1.72	.70	1.2
1.82	.72	1.3	2.16	1.71	3.7	2.16	.66	1.4
2.84	.56	1.6	3.01	1.29	3.9	3.59	.53	1.9
3.59	.47	1.7	3.46	1.21	4.2	3.79	.52	2.0
	Average	1.5		Average	3.9		Average	1.5
n-Octane			Octene-1			Heptene-1		
1.04	5.30×10^{-3}	5.5×10^{-3}	0.79	3.37×10^{-3}	2.7×10^{-3}	0.50	4.38×10^{-3}	2.2×10^{-3}
1.19	4.47	5.3	1.04	2.65	2.8	.76	2.97	2.3
1.48	3.56	5.3	1.48	1.91	2.8	1.04	2.20	2.3
2.02	2.56	5.2	1.82	1.34	2.4	1.21	1.91	2.3
2.64	1.92	5.1	2.70	.95	2.6	1.68	1.25	2.1
3.18	1.62	5.2	2.79	.95	2.7	2.43	.89	2.2
3.76	1.44	5.4	3.11	.90	2.8	3.76	.70	2.6
5.53	1.00	5.5	3.74	.78	2.9		Average	2.3
8.35	.80	$(6.7)^b$	8.82	.37	(3.3)			
12.01	.56	(6.7)		Average	2.7			
	Average	5.3						

^{a}k, product of pressure and fuel flow.

^{b}Average does not include values in parentheses.

TABLE II. - RATIO OF SMOKE-FREE FUEL FLOW

RATE OF n-OCTANE AND OCTENE-1 OVER A

PRESSURE RANGE OF 1 TO 10 ATMOSPHERES

Pres- sure, atm	Fuel flow, g/sec		Ratio of n-octane to octene-1
	n-Octane	Octene-1	
1	5.51×10^{-3}	2.75×10^{-3}	2.00
2	2.60	1.25	2.08
3	1.70	.88	1.93
4	1.34	.73	1.84
6	.98	.51	1.92
8	.80	.40	2.00
10	.67	[a].32	2.09

[a]Extrapolated value.
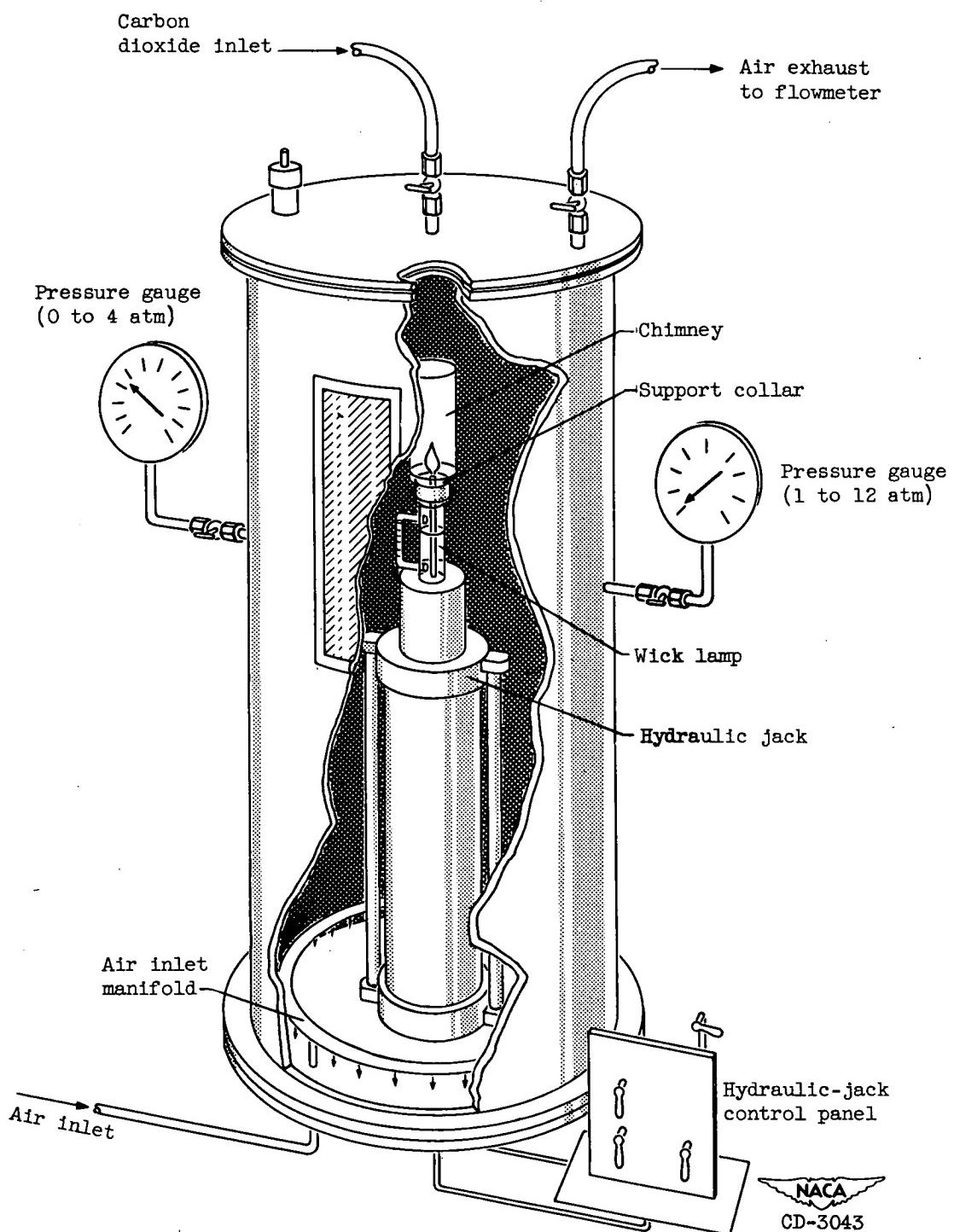
Figure 1. - Diagram of apparatus for determining smoking tendency.
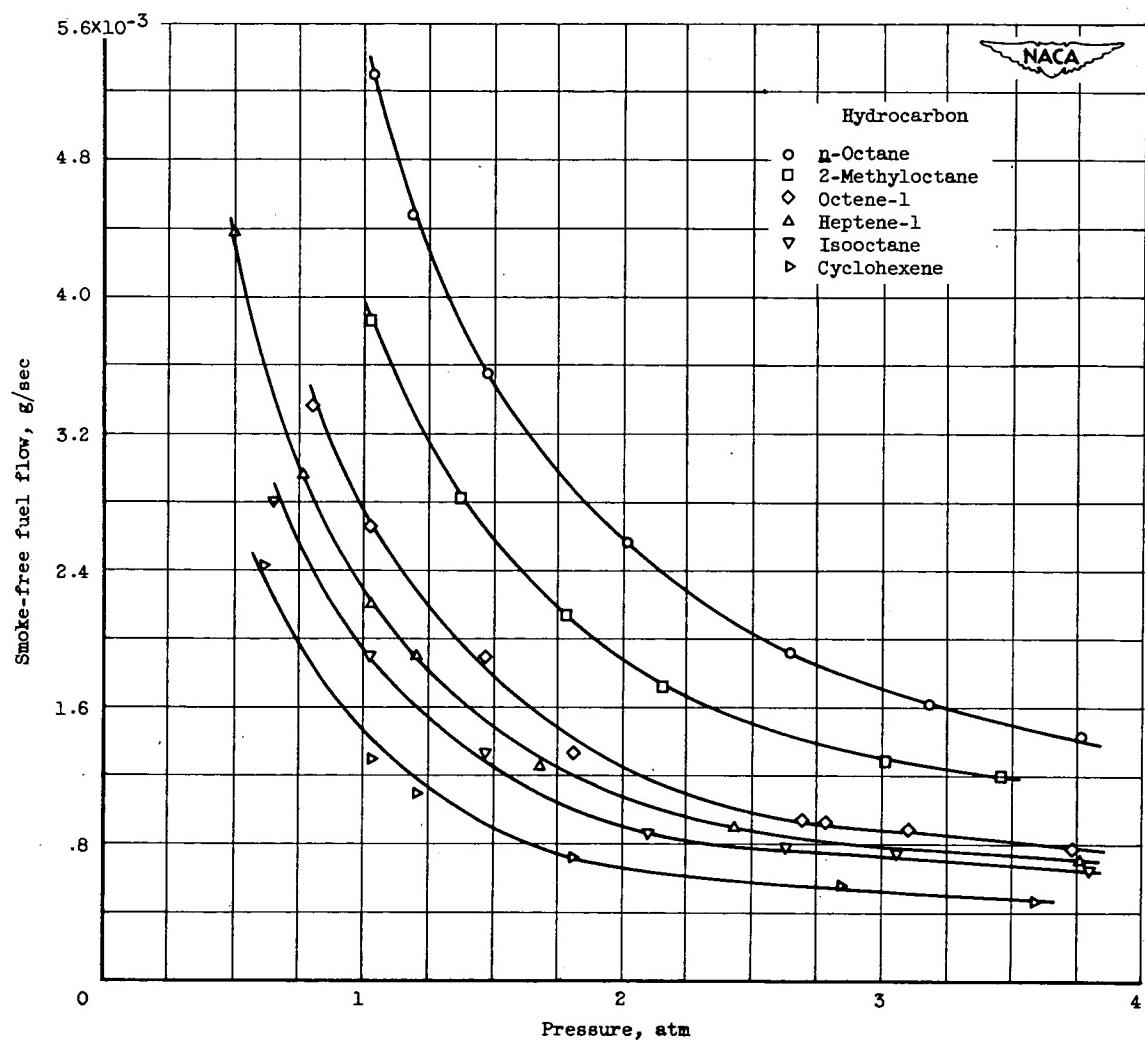
(a) Six hydrocarbons at pressures to 4 atmospheres.

Figure 2. - Variation in smoke-free fuel flow with pressure.
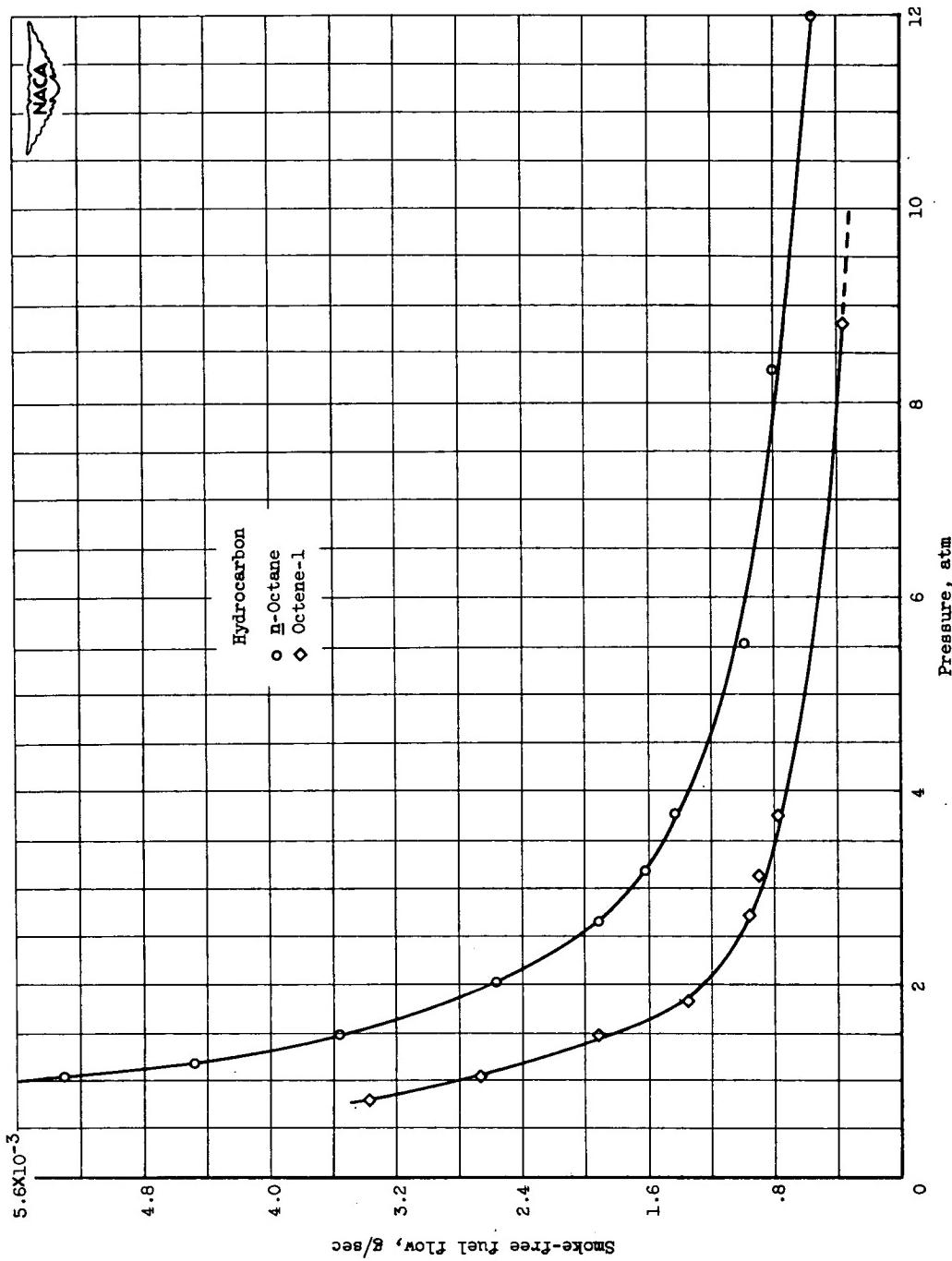
(b) Two hydrocarbons at pressures to 12 atmospheres.

Figure 2. - Continued. Variation in smoke-free fuel flow with pressure.
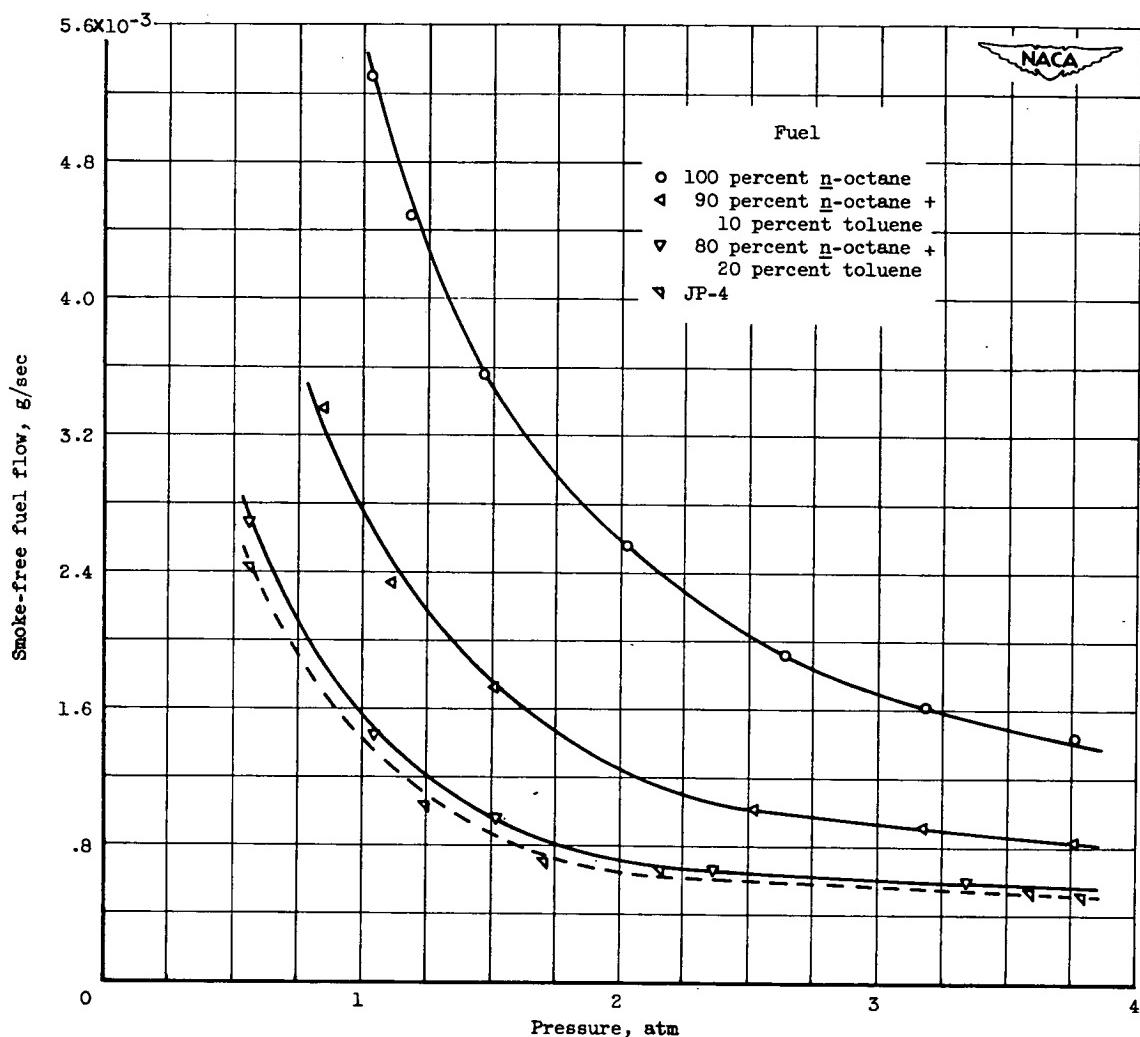
(c) Various fuels and blends at pressures to 4 atmospheres.

Figure 2. - Concluded. Variation in smoke-free fuel flow with pressure.
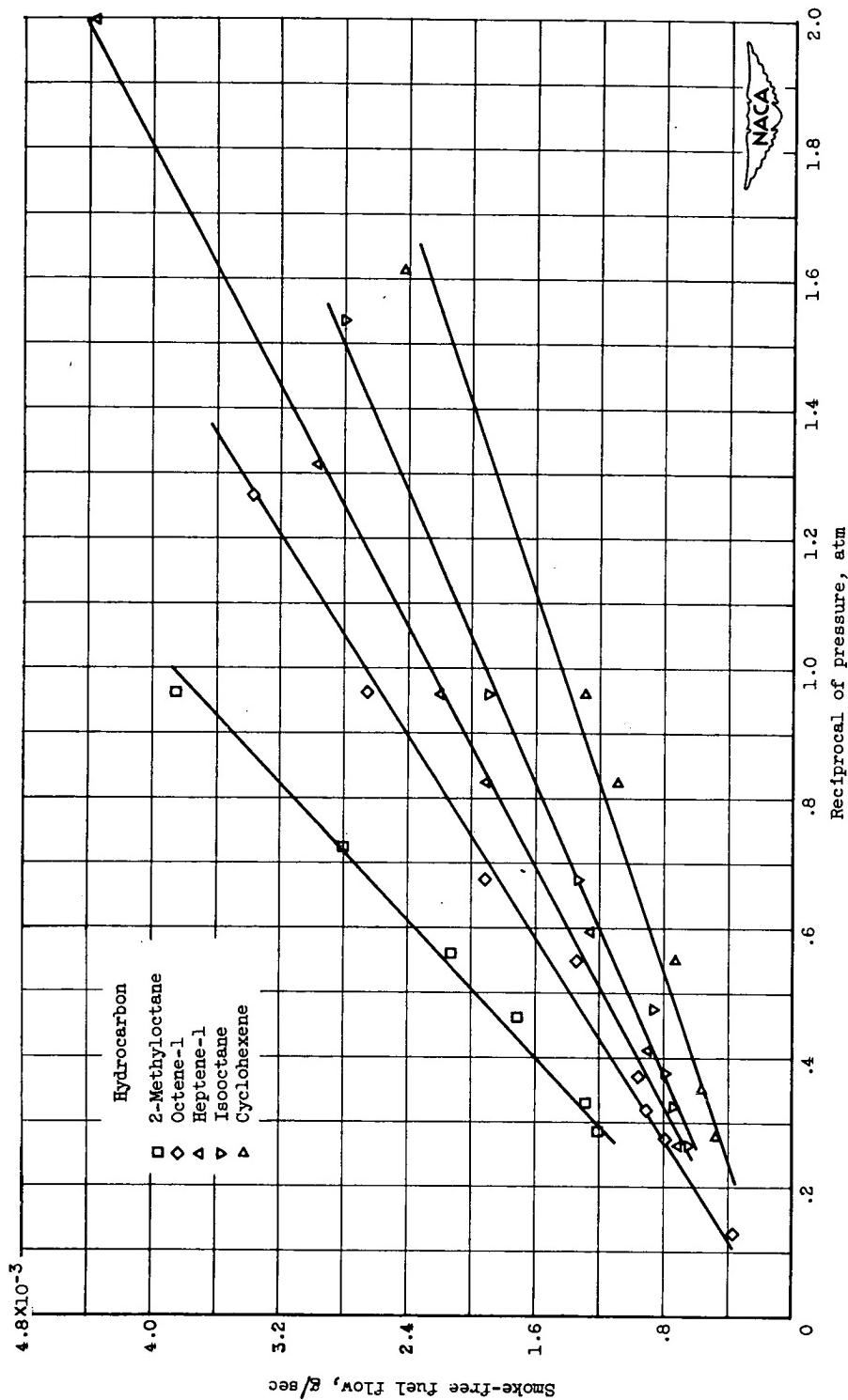
(a) Five hydrocarbon fuels.

Figure 3. - Smoke-free fuel flow against reciprocal pressure.

(b) Various fuels and blends.
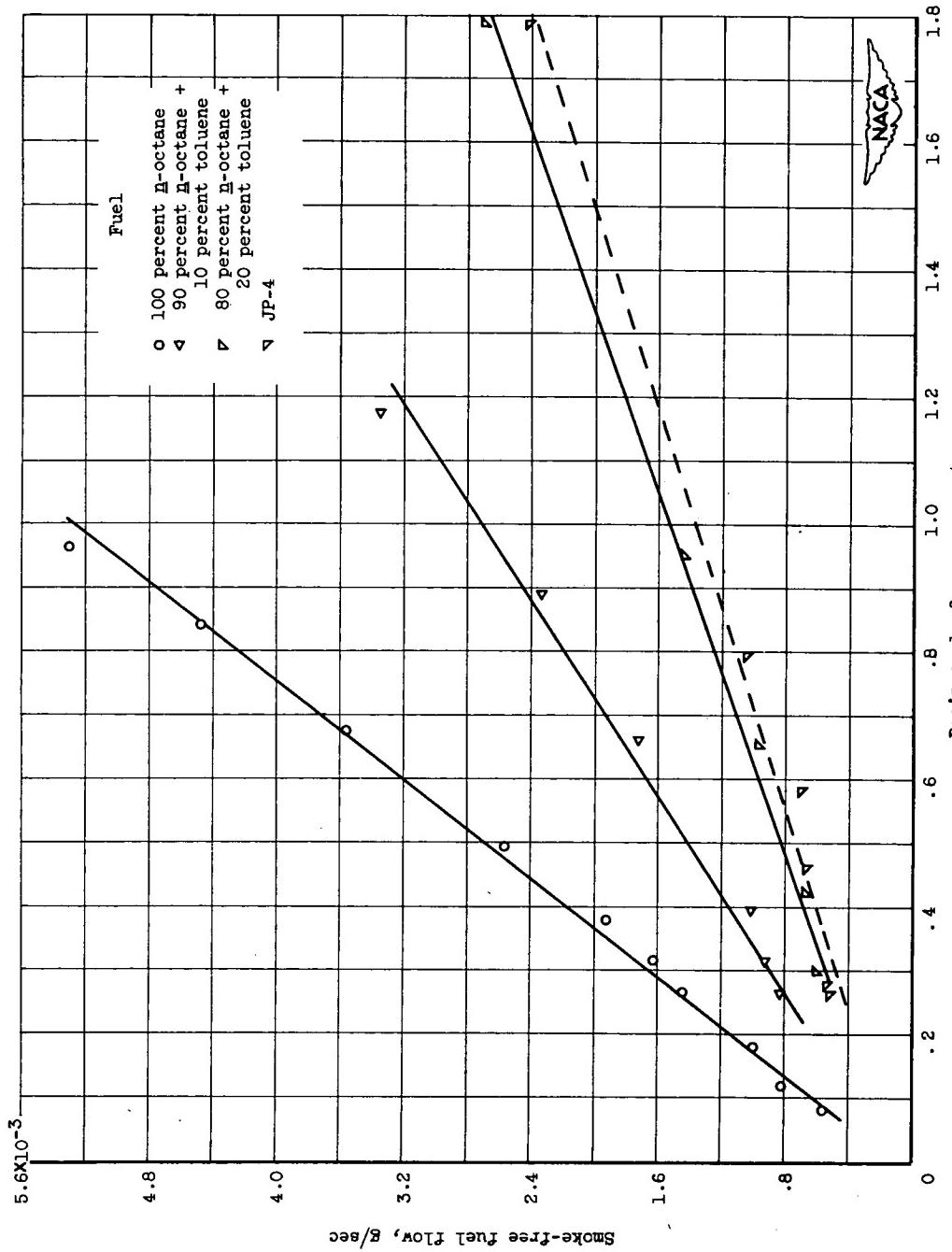
Figure 3. - Concluded. Smoke-free fuel flow against reciprocal pressure.